The Reddening of Red Supergiants: When Smoke Gets in Your Eyes

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ABSTRACT

Deriving the physical properties of red supergiants (RSGs) depends upon accurate corrections for reddening by dust. We use our recent modeling of the optical spectra of RSGs to address this topic. First, we find that previous broad-band studies have underestimated the correction for extinction in the visible, and hence the luminosities (if derived from V); the shift in the effective wavelengths of the standard B and V bandpasses necessitates using an *effective* value of the ratio $R'_V = 4.2$ to correct broad-band photometry of RSGs if $R_V = 3.1$ for early-type stars viewed through the same dust, where we have assumed the standard reddening law of Cardelli, Clayton, & Mathis (1989). Use of the Fitzpatrick (1999) reddening law would lead to $R'_V = 3.8$, as well as slightly lower values of extinction derived from spectrophotometry, but results in slightly poorer fits. Second, we find that a significant fraction of RSGs in Galactic OB associations and clusters show up to several magnitudes of excess visual extinction compared to OB stars in the same regions; we argue that this is likely due to circumstellar dust around the RSGs. We also show that the RSG dust production rate (as indicated by the 12-μm excess) is well-correlated with bolometric luminosity, contrary to what has been found by earlier studies. The stars with the highest amount of extra visual extinction also show significant near-UV (NUV) excesses

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compared to the stellar models reddened by the standard reddening law. This NUV excess is likely due to scattering of the star's light by the dust and/or a larger average grain size than that typical of grains found in the diffuse interstellar medium. Similar excesses have been attributed to circumstellar dust around R Coronae Borealis stars. Finally, we estimate that the RSGs contribute dust grains at the rate of $3 \times 10^{-8} M_{\odot}$ yr^{-1} kpc^{-2} in the solar neighborhood, comparable to what we estimate for late-type WCs, $1 \times 10^{-7} M_{\odot}$ yr^{-1} kpc^{-2}. In the solar neighborhood this represents only a few percent of the dust production (which is dominated by low-mass AGBs), but we note that in low-metallicity starbursts, dust production by RSGs would likely dominate over other sources.

Subject headings: stars: atmospheres—stars: fundamental parameters—stars: late-type—supergiants—dust, extinction

1. Introduction

Red supergiants (RSGs) are the evolved, He-burning descendents of moderately massive ($\leq 40 M_{\odot}$) O and B stars. We have recently used the new generation of MARCS stellar atmosphere models (Gustafsson et al. 1975, 2003; Plez et al. 1992) to fit optical spectrophotometry of 74 Milky Way RSGs, from which we derived a new effective temperature scale for RSGs of Galactic metallicity (Levesque et al. 2005, hereafter Paper I). A subsample of 62 of these stars belong to OB associations with known distances, which allowed us to determine other physical properties, such as bolometric luminosity and stellar radii, for comparison with those predicted by stellar evolutionary models. We found excellent agreement, thus removing a major discrepancy between "observation" and theory for massive star evolution (see Massey 2003).

However, that study underscored the difficulty in correcting for reddening due to dust for these objects; our work hinted at several previously neglected problems, which we consider more fully here. First (Sec. 2), we find that previous efforts involving broad-band filter photometry have led to systematically underestimating the visual extinctions, and thus to underestimating the stellar luminosities. Although we successfully avoided that problem in Paper I by using spectrophotometry to derive reddenings, our work revealed that many of these stars suffer extinction beyond that of their neighboring O and B stars. We show here (Sec. 3) that this is likely caused by circumstellar dust from these "smoky" stars. Although future studies will attempt to derive the reddening law for this dust, it is already clear that the circumstellar dust results in a near-UV excess compared to the stellar models reddened with the "standard" reddening law (Sec. 4). Finally, we use the results of Paper I and the

current study to estimate the fraction of dust deposited in the diffuse interstellar medium compared to that of other sources in the Galaxy (Sec. 5).

2. The Effective R_V for Broad-band Photometry of RSGs

A knowledge of the ratio of total to selective extinction $R_V \equiv A_V/E(B-V)$ is needed in order to derive physical parameters of reddened stars. Using *early-type* stars with moderate reddenings in the Milky Way, Sneden et al. (1978) and others found R_V to be typically 3.1, although it is now well understood that this value is not universal in nature, but represents the average sightline through the diffuse interstellar medium (Valencic et al. 2004). Values of $R_V \sim 5$ and even higher have been found for stars in dense molecular clouds; see, for example, Cardelli & Wallerstein (1989) and Cardelli et al. (1989, hereafter CCM89). These *physical* variations of R_V are due to differences in the line-of-sight environment, such as the grain size distribution.

However, aside from such real differences in the dust properties, one must employ a larger *effective* value of R_V (which we will denote as R'_V) when correcting broad-band photometry of objects whose spectral energy distributions differ from that of lightly- to moderately-reddened O stars. This is simply due to the shift of the effective wavelength of the filters compared to that obtained with early-type stars. A very red star shifts the effective wavelengths of the B and V filters to longer wavelengths, where extinction is less, making both A_B and A_V smaller for a given amount of dust. The net effect of lowering A_B and A_V is to *increase* R'_V, as the decrease in the denominator of the ratio outweighs the decrease of the numerator. McCall (2004) has recently emphasized the importance of considering the spectral energy distribution (SED) of the source when correcting for extinction in galaxy photometry, as their SEDs do not, after all, resemble that of the OB stars for which the extinction laws were derived.

We avoided this problem in Paper I by using spectrophotometry of the stars to measure the color excess with regard the MARCS models, employing the CCM89 reddening law. Since neither the B nor V filters were actually used in our color excesses, conversion to A_V was straight-forward, although it did assume that the reddenings had a "typical" $R_V = 3.1$ value. For broad-band photometry of RSGs, a value of $R'_V = 3.6$ has usually been adopted (Lee 1970, Humphreys 1978), and is consistent with the scaling of R'_V with color proposed by Schmidt-Kaler (1982). However, our work in Paper I has forced us to conclude that this value is not very accurate, as it produced A_V values that were systematically smaller than extinction values derived from our spectrophotometry. We have derived an improved value for the effective R'_V of RSGs by convolving the MARCS models with the standard B and

V band-passes (Bessell 1990). We used the CCM89 reddening law with $R_V = 3.1$ to add various amounts of reddening to the model spectra; we then computed the resulting change in the flux in the V filter to find A_V, and the differences in the relative fluxes in the B and V filters (compared to the no-reddening case) in order to determine $E(B-V)$. The effective value of $R'_V = A_V/E(B-V)$ then follows directly. We found that there is a significant dependence upon the assumed surface gravity $\log g$ in the sense that stars with higher $\log g$ (0.5) produce lower R_V values; the value $R'_V = 3.6$ usually used for RSGs is actually more appropriate to the surface gravities of red dwarfs or giants. There is very little dependence of R'_V on effective temperature in this regime. This is not surprising, as it is well known that $B-V$ is primarily sensitive to surface gravity rather than temperature for RSGs; see discussion in Massey (1998). Stars with higher reddenings require a slightly higher R'_V value. In summary, for stars with $\log g$ between -0.5 and 0.5, $T_{\rm eff}$ between 3400 and 4200 K, and $E(B-V) \leq 3$, we find

$$R'_V = 4.1 + 0.1E(B-V) - 0.2 \log g.$$

For a "modestly" reddened RSG, a value of $R'_V = 4.2$ is thus appropriate. As shown in Fig. 1, this value for R'_V now brings the extinction derived from broad-band photometry into accord with that derived from spectrophotometry.

We were initially concerned about such a large value for R'_V, but found that we derive a very similar number using the Kurucz (1992) ATLAS9 models in place of the MARCS models. We also find a large R'_V value when we instead employ the Fitzpatrick (1999) reddening law with the MARCS models: $R'_V = 3.8 - 0.2 \log g$, with a negligible correction for color excess $E(B-V) \leq 3$. The Fitzpatrick (1999) law has slightly lower extinction than CCM89 on the short wavelength side of the B filter, and on the long wavelength side of the V filter; the latter is primarily responsible for the difference in the derived R'_V. Fitzpatrick (1999) has emphasized the difficulties encountered in deriving a monochromatic law from broad-band photometry, and derived a reddening curve that was very similar to that of CCM89; but for stars of extreme color, such as RSGs, small differences matter. To obtain satisfactory fits to our spectrophotometry using the Fitzpatrick (1999) reddening law we found that we needed to decrease the visual extinction by about 0.3 mag compared to that needed with the CCM89 law. Even so, the CCM89 law (used in Paper I) resulted in slightly better fits, as shown by the two examples in Fig. 2. To answer which reddening law is really "right" requires careful comparison with spectrophotometry of stars over a wide range of properties. Here we simply note that the 0.3 mag systematic differences obtained between these two laws are comparable to the estimated uncertainties in Paper I.

3. Evidence for Circumstellar Dust Extinction

Although our spectrophotometry was immune to issues of bandpass shifts, it still supposed that the extinction was due to $R_V = 3.1$ reddening that characterizes dust in the diffuse interstellar medium. That assumption was probably not completely valid, as circumstellar dust may be present in some cases. We began to consider this possibility when we were struck by the fact that many of the RSGs in OB associations have significantly higher extinction than the average early-type star in the same regions. In Fig. 3 we show the comparison between the two. The average A_V for each cluster comes from Paper I, and is based upon a critical inspection of the values listed in Humphreys (1978), eliminating stars whose spectroscopic parallaxes are significantly (1 mag) deviant from the cluster averages. Indeed, this conclusion could have been made by others based purely on those data. Of course, many of the OB associations cover a large area of the sky and include a significant range of reddenings, and we indicate the standard deviation by the error bars ($\pm 1\sigma$) in Fig. 3. We find that about 40% of our sample (22 out of 56 stars) shows evidence of extra extinction at the $> 1\sigma$ level; 14% (8 out of 56) shows $> 3\sigma$ excess extinction.

In retrospect, this result should have been long anticipated. Red supergiants are known to be "smoky" in the sense that dust condenses in the stellar winds. The presence of the resulting circumstellar dust shells was first revealed by ground-based IR photometry (see, for example, Hyland et al. 1969), while *IRAS* two-color diagrams established that such dust shells are a common phenomenon for RSGs (Stencel et al. 1988, 1989). This dust is thought to be partially responsible for driving the stellar wind via radiation pressure (but see the questions raised by MacGregor & Stencel 1992). Interferometry in the IR has demonstrated that for some RSGs (such as VY CMa) the dust is found very close to the star itself (3-5 stellar radii), while in other cases it is found at greater distances, suggesting that the production of substantial amounts of dust is episodic in nature, with time scales of a few decades (Danchi et al. 1994).

Josselin et al. (2000) use the K_o-[12] color to determine dust-productions rates $\dot{M}_d$, where [12] is the magnitude based on the IRAS 12μm flux adjusted so that a 10,000 K star would have zero color. (Thus stars with positive K_o-[12] values have some 12-μm excess, as the index has little sensitivity to effective temperature.) One of the surprising results from that study was that there was little or no correlation of $\dot{M}_d$ with bolometric luminosity. From first principles one would expect that mass-loss rates will be dependent upon luminosity, among other factors. However, Josselin et al. adopted the individual spectroscopic parallaxes listed by Humphreys (1978) as the true distances, rather than using the average cluster values. This is equivalent to adopting a single absolute visual magnitude for all RSGs of a given spectral type and luminosity class, a poor approximation since RSGs span a large range in

masses and luminosities. We revisit this issue here by using the cluster distances adopted in Paper I (based upon the early-type stars), and by revising the $\dot{M}_d$ values using the larger and more homogeneous K dataset of the 2Mass point source catalog. Fig. 4(a) shows a more convincing correlation. The scatter is still large, but in part this may be due to the inclusion of a few unreliable data points: for instance, the two outliers on the left are HD 160371 in M6, a cluster which contains no early-type members (Humphreys 1978), and BD+56°2793 (ST Cep) in Cep OB2, which Humphreys (1978) characterizes as a "doubtful member" of its association. In Figs. 4(b) and (c) we show that the extra extinction ΔA_V is correlated with $\dot{M}_d$ and with $M_{\rm bol}$.

We can also ask if this amount of extinction is *reasonable* given the measured dust production rates. Equation 3.31 from Whittet (2003) provides the link between the mass density of dust $\rho_{\rm d}$ and A_V per unit path-length L: $\rho_d = 3.1 \times 10^{-4}(A_V/L)$, where the density and length are in MKS units. A rigorous calculation for dust condensing around RSGs is complicated by the fact that the dust may be decoupled from the stellar wind gas velocities (MacGregor & Stencel 1992) and likely occurs episodically (Danchi et al. 1994), and thus the radial distribution of dust throughout the $10^5 - 10^6$ yr lifetime of the RSG phase is not easily known. However, *most* of the extinction will occur in the thin shell near where the dust first condenses, as this is where the mass density will be the highest. We can therefore get a crude lower-limit to the expected amount of extinction by assuming a thin-shell approximation: $A_V = \Delta R \times 3.2 \times 10^3 \times M_d/(4\pi R^2 \Delta R)$, where R is the radius (meters) where the dust condenses, M_d is the mass (kg) of the dust, and the shell thickness ΔR is substituted for the path length L, which cancels with ΔR in the denominator. For 10 yrs of dust production (a typical time scale for episodic dust formation according to Danchi et al 1994) at a rate of $10^{-8} M_\odot$ yr^{-1}, we would expect a mass of 2×10^{23} kg to be deposited in this thin shell, and thus we would have $A_V = 1.0$ mag, where we have adopted a radius R of $10^4 R_\odot$ (i.e., 10 stellar radii). Dust produced over a longer period of time, or which condenses at a smaller radii, will increase this "minimum reasonable value", while a lower dust production rate, or a larger R, will reduce the value. This exercise suggests that for the lower luminosity RSGs, ΔA_V would be a few tenths of a mag or less (and hence not detectable), while the most extreme RSGs might have ΔA_V values of several magnitudes—just what we find.

4. Dust in the Near-UV

Sufficient dust to cause several mags of visual extinction might make its presence known in ways other than the IR excess discussed above. R Coronae Borealis stars, whose extreme variability is known to be due to circumstellar dust, show a UV-excess (Hecht et al. 1984,

1998). In part, such "fresh" dust may start with a distribution skewed to larger particle sizes (which would lead to less UV and NUV extinction) before being broken down and assimilated into the interstellar medium (see also Jura 1996 and Whittet 2003). Alternatively, preferential scattering of blue light into the beam by the parts of the unresolved circumstellar dust shell that are off-axis to the line of sight may be enough to explain the larger observed fluxes in the UV and near-UV regions.

Indeed, as we reported in Paper I, the MARCS models reddened with an $R_V = 3.1$ CCM89 law showed this sort of NUV mismatch with the observed spectral energy distributions for the most heavily reddened stars (which were also the ones with the highest excess reddening). However, we could not completely rule out an observational explanation for the discrepancy, given that even a small amount of red light scattered within the instrument could contaminate the low fluxes in the NUV without such problems showing up in the spectrophotometric standards. For the most reddened M supergiants in our sample, $F_{\lambda 7000}/F_{\lambda 3500}$ is 10,000, while this ratio is near unity for standards.

On UT 2005 April 21 we obtained new data in the blue (3500-5800Å) on a subsample of 11 stars from Paper I using the Kitt Peak 2.1-m telescope with the GoldCam spectrometer. The observational parameters are the same as given in Table 3 of Paper I *except* that a $CuSO_4$ filter was employed to eliminate any possibility of contamination of the NUV region by red light. The observational and reduction procedures were the same as given in Paper I. The new spectra agreed well with the old data in general, although turns-ups in the blue for the two reddest stars are now eliminated, suggesting that instrument effects could indeed have been a problem with some of those data. We therefore restrict our discussion only to the new data.

In Fig. 5(a) and (b) we show the match between the models reddened by the standard CCM89 $R_V = 3.1$ law and the observed spectra for two of the stars in our sample. KY Cyg has the the highest excess reddening ($\Delta A_V = 4.9$ mag), and is among the most luminous star in our sample ($M_{\rm bol} = -8.8$). The discrepancy in the NUV is striking. By contrast, the agreement in the NUV region is very good for the star HD 216946, a star with no excess reddening ($\Delta A_V = 0.0$) and modest luminosity ($M_{\rm bol} = -5.5$). We can quantify this by computing an NUV index where we compare the integrated flux from 3500 to 3900Å of the reddened model to that of the star, expressed as a difference in magnitudes. In the other panels of Fig. 5 we show that the size of the NUV discrepancy is well correlated with the amount of extra extinction (Fig. 5*c*), the dust production rate $\dot{M}_d$ as measured from the 12-μm excess (Fig. 5*d*), and the bolometric luminosity of the star computed from the K-band (Fig. 5*e*).

There are certainly other explanations for the NUV discrepancy. The spectra of some

stars could be contaminated by the presence of a hot companion. However, we would expect such stars to show a composite spectrum. Indeed, in Paper I we had eliminated several stars from our sample because Balmer lines were clearly present. Another intriguing possibility is that hot spots might be present on the surface of these stars, as suggested by interferometric observations and UV *HST* imaging; see Freytag (2003) and references therein. Stars with vigorous convection patterns could have spectra dominated by regions at different temperatures depending upon the wavelength. Alternatively, chromospheric emission may play a role (Carpenter et al. 1994, Harper et al. 2001). These possibilities could, and should, be investigated by higher spectral resolution studies. Nevertheless, the correlations shown in Fig. 5 provide strong evidence that circumstellar dust is the culprit.

Although it is tempting to derive the reddening law of this circumstellar material, it is difficult to accurately extract the circumstellar component from the total extinction, given the high (and uncertain) amount of foreground reddening. We are in the process of obtaining the necessary data for a large sample of RSGs in the Magellanic Clouds. There the problem is actually tractable, given the small and relatively uniform extinction of the Clouds (van den Bergh 2000).

5. Contribution to the Dust Content of the Milky Way

In reviews of the origin of cosmic dust, the role of RSGs is often ignored, with the primary sources given as SNe and low-mass AGB stars. However, for dusty galaxies at large look-back times, AGBs cannot play a role given the time scales for low-mass stellar evolution. When high-mass stars are discussed, it is usually only the WC-type Wolf-Rayet stars that are considered (see, for example, Dwek 1998). However, only the late-type WCs are known to produce dust, and even those types may require a binary companion (see Crowther 2003). In the Milky Way, late-type WCs are concentrated towards the Galactic center, and are known to be absent in low-metallicity galaxies (see Massey 2003 and references therein). So, in extreme environments (such as metal-poor starbursts, or for most galaxies at early times), RSGs could play a dominant role.

Here we briefly consider how large that role is locally. We expect the production rate (in units of mass per unit time per unit area of the galactic disk) to be

$$R_{\rm RSG} = \int_{10}^{25} \rho_{\rm RSG}(m)\ \dot{M}_d(m)\ dm,$$

where $\rho_{\rm RSG}(m)$ is the surface density of RSGs as a function of mass and $\dot{M}_d(m)$ is the dust production rate. We can estimate these quantities as follows. First, from Fig. 4(a), we

find that $\log \dot{M}_d = -0.43 \times M_{\rm bol} - 12.0$ for $M_{\rm bol} < -5$, which roughly corresponds to masses $> 10M_\odot$. In Paper I we used the evolutionary tracks of Meynet & Maeder (2003) to estimate that the masses of RSGs scale with luminosity as $\log(M/M_\odot) = 0.50 - 0.099M_{\rm bol}$, so we expect

$$\log \dot{M}_d = 4.3 \log(M/M_\odot) - 14.2$$

for RSGs with masses $10 < (M/M_\odot) < 25$. The surface density $\rho_{\rm RSG}(m)$ is harder to estimate. We expect $\rho_{\rm RSG}(m) \propto m^{-2.35}\Delta\tau_{\rm RSG}(m)$, where we have assumed a Salpeter initial mass function, and $\Delta\tau_{\rm RSG}$ is the lifetime of the RSG phase as a function of mass. From the evolutionary models of Meynet & Maeder (2003), we find that the RSG phase lasts 2 Myr ($10M_\odot$) to 0.4 Myr ($25M_\odot$), and we use the models to approximate $\log \Delta\tau_{\rm RSG} = 8.1 - 1.8 \log(M/M_\odot)$. Jura & Kleinmann (1990) find 21 *high-luminosity* ($M_{\rm bol} < -7.8$, corresponding roughly to $19M_\odot$) RSGs within 2.5 kpc of the sun, or a surface density of 1 kpc^{-2}. If that is complete (and we list a comparable number, 18, meeting these criteria in our admittedly incomplete sample from Paper I), then we can use that to determine the scaling factor C: $\int_{19}^{25} \rho_{\rm RSG}(m)\, dm = 1.3 \times 10^8 C \int_{19}^{25} m^{-2.35}\, m^{-1.8}\, dm = 1$, or $C = 4.5 \times 10^{-4}$. Thus $\rho_{\rm RSG}(m) = 5.8 \times 10^4 m^{-4.15}$. Substituting in the above, we expect

$$R_{\rm RSG} = 3.7 \times 10^{-10} \int_{10}^{25} m^{0.15}\, dm,$$

or 8.5 $10^{-9} M_\odot$ yr^{-1} kpc^{-2}.

We emphasize that this value is uncertain due primarily to our poor understanding of the exact completeness limits. We can instead derive the surface density of RSGs using what we do know about the surface densities of other types of massive stars in the solar neighborhood, appealing to the evolutionary models to then connect the two. Although the number of O-type stars within a few kpc of the sun is poorly known (see Massey 2003), the number of WC-type Wolf-Rayet stars *is* thought to be complete, given their strong emission-line signature (Massey & Johnson 1998). According to the evolutionary models of Meynet & Maeder (2003), WCs come from stars with masses greater than $40M_\odot$; the lifetime of the WC stage is independent of mass, with $\Delta\tau_{\rm WC} = 0.2$ Myr (see their Fig. 10). The surface density of WCs in the solar neighborhood is 2.1 kpc^{-1}, a number which we believe *is* based on a complete sample (Massey 2003 and references therein). So, $\int_{40}^{120} \rho_{\rm WC}(m)\, dm = 2 \times 10^5 C \int_{40}^{120} m^{-2.35}\, dm = 2.1$, and we derive $C = 2.7 \times 10^{-3}$, about a factor of 6 times greater. Thus $R_{\rm RSG} = 5.1 \times 10^{-8} M_\odot$ yr^{-1} kpc^{-2}. Given the uncertainties (both in our knowledge of the local RSG content, and in the models) we consider this agreement very good, and adopt a value $R_{RSG} = 3 \times 10^{-8} M_\odot$ yr^{-1} kpc^{-2}. For comparison Whittet (2003) estimates a return rate for RSGs that is about 3 time greater, well within the uncertainties of our approximation. This is about 1% of the rate of return of AGBs.

How does this compare to the production rate for WC-type WRs? As stated above, only the late-type WCs (WCLs) are known to produce dust, and even those may require a binary companion. From Conti & Vacca (1990) we find a surface density of WCLs of 0.5 kpc^{-1}. The (total) mass-loss rates of WCs are about independent of mass, and are about $10^{-4.8} M_\odot\ \mathrm{yr}^{-1}$ (Nugis & Lammers 2000). Of this, perhaps 2% is dust (Dwek 1998). So we expect $R_{\mathrm{WCL}} = 1.5 \times 10^{-7} M_\odot\ \mathrm{yr}^{-1}\ \mathrm{kpc}^{-2}$. If close binarity is a requirement for dust ejection, then this value should be decreased by roughly a factor of 2. We adopt a compromise of $R_{\mathrm{WCL}} = 1 \times 10^{-7} M_\odot\ \mathrm{yr}^{-1}\ \mathrm{kpc}^{-2}$, or about a factor of 3 higher than R_{RSG}. In low-metallicity systems (or the outwards of the solar circle in the Milky Way) there are no late-type WCs, and RSGs will dominate the dust production by massive stars. In star-bursts, where stars are recently formed, most dust production should be by RSGs, as low-mass stars will not have had sufficient time to evolve to AGBs.

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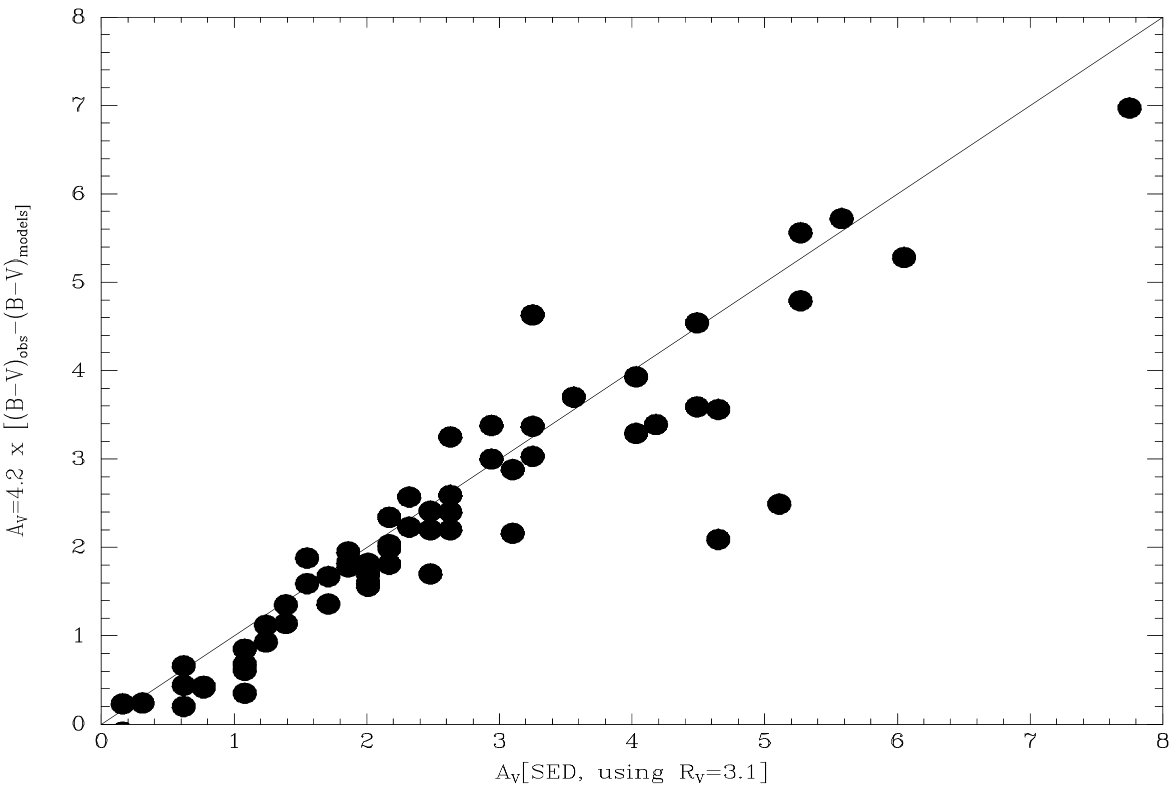

Fig. 1.— Comparison of visual extinction A_V. The extinction derived from broad-band photometry and $R_V = 4.2$ is compared with that derived from the spectral energy distribution and $R_V = 3.1$.

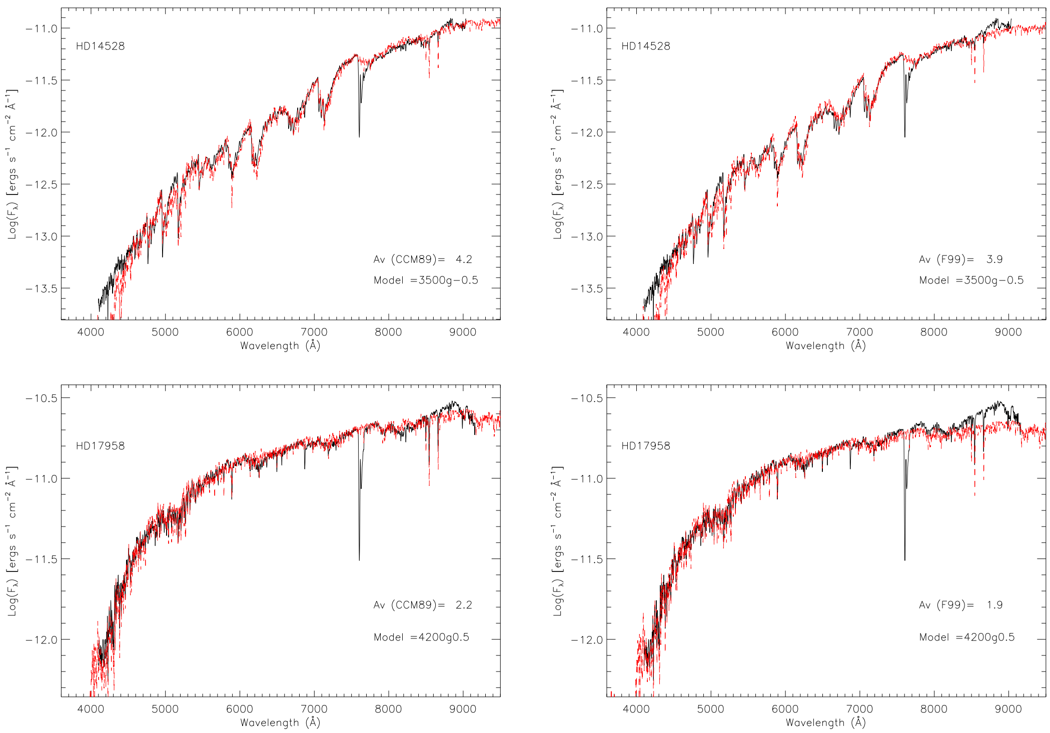

Fig. 2.— Comparison of the fits obtained CCM89 and Fitpztrick (1999, hereafter F99) reddening laws. In the top two panels, we compare the fits for HD 14528 (M4.5 I) using the MARCS 3500g-0.5 model reddened by (a) CCM89 with $A_V = 4.2$ and (b) F99 with $A_V = 3.9$. In the bottom two panels, we make a similar comparison for HD 17958 (K2 I) by reddening the MARCS 4200g0.5 model using (c) CCM89 with A_V=2.2, and (d) F99 with $A_V = 1.9$. Similar fits are obtained using CCM89 and F99, although the agreement is slightly better in the far red with the CCM89 law. The strong, unfit feature at 7600Å is the telluric A-band, and the turndown at 8900Å is also due to telluric absorption.

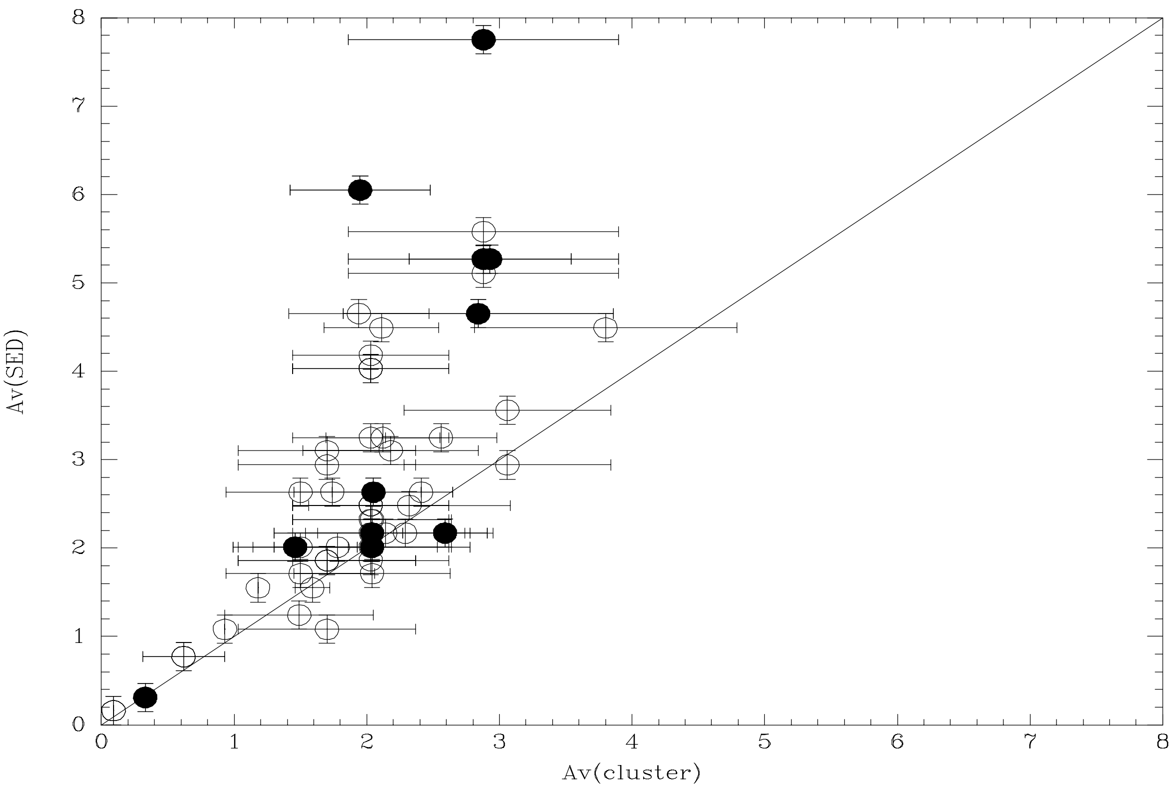

Fig. 3.— Extinction A_V of RSGs compared to that of early-type stars in the same clusters. The error bars denote the (1σ) spread of extinction in each cluster and uncertainty in the A_V from our fitting procedure in Paper I. The filled circles denote the stars for which we have new data in the near-UV.

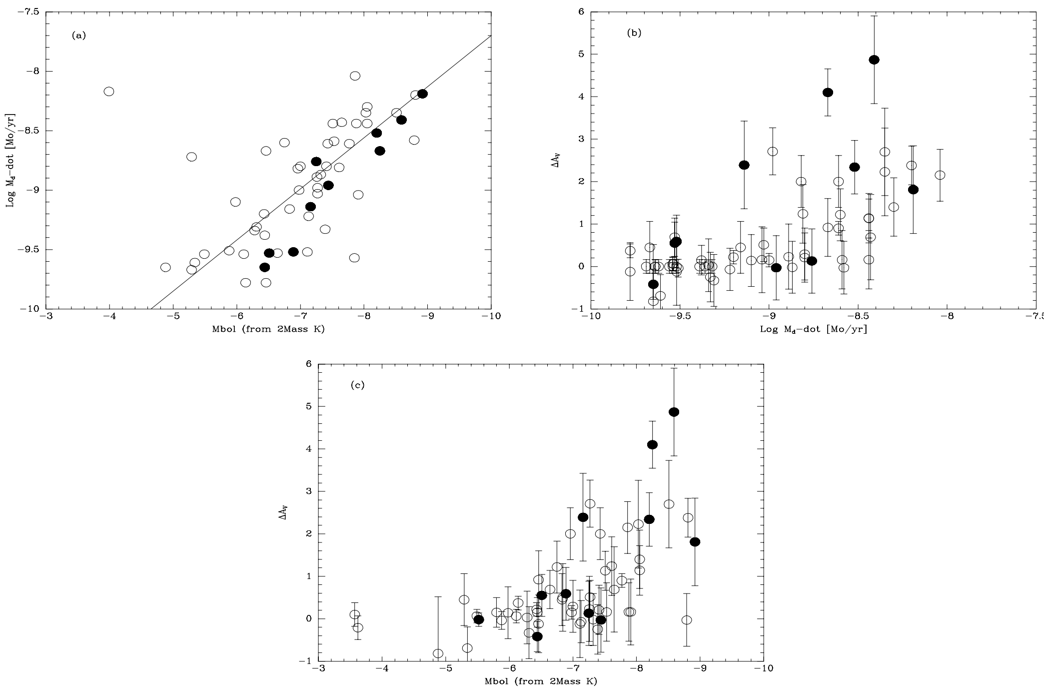

Fig. 4.— The correlation of excess reddening with dust. In (a) we show that the dust production rate $\dot{M}_d$ (revised from Josselin et al. 2000) is correlated with bolometric luminosity. The solid line is the least-squares fit $\log \dot{M}_d[M_\odot \text{ yr}^{-1}] = -0.43 M_{\rm bol} - 12.0$ excluding four outliers, which are not considered further. In (b) we compare $\dot{M}_d$ with the excess extinction ΔA_V. Stars with low dust production rates have extinction that is more in keeping with that of the early-type stars in the same OB associations; stars with higher dust production rates also tend to show excess extinction. In (c) we compare the excess extinction ΔA_V to the bolometric luminosity determined from K. In all three plots the filled circles indicate the stars for which we have new data in the near-UV.

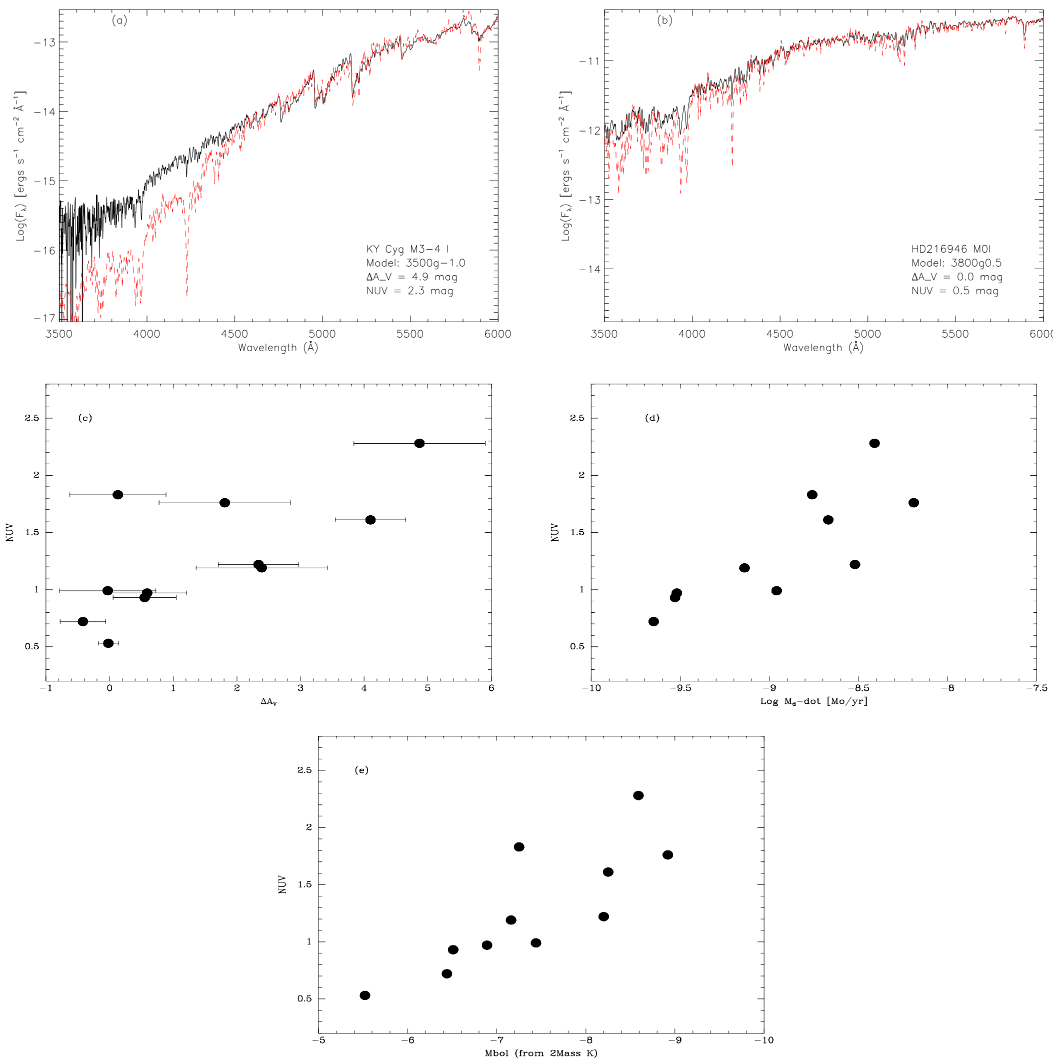

Fig. 5.— The effect of dust in the NUV. In (a) and (b) we show the match between the observations (black solid line) and the reddened MARCS model (dashed red line) for KY Cyg and HD 216946. The former shows considerable extra flux in the NUV compared to the reddened model; the latter does not. In (c), (d), and (e) we show the correlation of the NUV index to the extra extinction ΔA_V, the dust production rate $\dot{M}_d$, and the bolometric luminosity computed from the K-band, respectively.